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Bradley Fighting Vehicle: Heat in the Driver's Compartment

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14. ABSTRACT *(Maximum 200 words)*:

This paper reports some preliminary efforts to document heat issues in the M2A3 Bradley Fighting Vehicle. This research compared surface and ambient temperatures throughout the driver compartments of the M2A3 and its predecessor, the M2A2 ODS (Operation Desert Storm) vehicle. Reports by Bradley Fighting Vehicle personnel had suggested that the M2A2 ODS was hot, but that the M2A3 was hotter. Results of this study supported these reports. Surface temperature measurements indicated that radiant heat through engine-adjacent areas of the driver's compartment of the M2A3 produced extreme heat levels that were substantially hotter than the M2A2 ODS, although both models were found to have extremely high levels of heat in these areas. This study provided empirical evidence for a primary source of excessive heat within the M2A3 Bradley Fighting Vehicle driver's compartment. One of the possible engineering solutions to reduce heat in the driver's compartment suggested was implemented on a trial basis. Additional temperature readings on an insulated vehicle indicated that the insulation significantly reduced the heat coming from the engine area to the driver.

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Bradley Fighting Vehicle (BFV) Driver

Heat stress

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FOREWORD

The U. S. Army Research Institute for the Behavioral and Social Sciences (ARI) Infantry Forces Research Unit at Fort Benning has conducted research on the Bradley Fighting Vehicle (BFV) for over twenty years. Much of this research has been on Bradley training and training devices, but there have been occasional ventures into human factors and engineering problems. ARI therefore has a broadly based research foundation in the BFV. Early in the fielding of the newest Bradley, the M2A3 vehicle, the Commanding General of the U.S. Army Infantry School and Center at Fort Benning requested that ARI provide technical advisory service in review of issues related to heat in the Bradley driver's compartment.

ARI personnel interviewed Bradley subject matter experts and performed limited hands-on measurements of driver compartment heat both at Fort Benning, and at Fort Hood where the first units were receiving Bradley M2A3 training. The heat problem and its apparent cause, poor insulation of the engine compartment wall, were evident. Results were briefed to the Bradley Training and Doctrine Command (TRADOC) Systems Manager, and to the Project Manager, Bradley Fighting Vehicle Systems (BFVS). As a result, the immediate interim solution to the identified problem, refitting Bradleys with increased insulation between the driver and the engine, was undertaken on a test basis. The effects of the insulation are promising and indicate a possible solution to the excessive heat in the Bradley.

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BRADLEY FIGHTING VEHICLE: HEAT IN THE DRIVER'S COMPARTMENT

EXECUTIVE SUMMARY

Research Requirement:

The Commanding General of the U.S. Army Infantry School and Center asked the U. S. Army Research Institute for the Behavioral and Social Sciences (ARI) Infantry Forces Research Unit to investigate some issues related to the new M2A3 Bradley Fighting Vehicle. The primary focus was on the driver's compartment, as Bradley crewmen were reporting that the new vehicle was too hot inside, hotter even than earlier versions of the vehicle. Tests done at Aberdeen Proving Ground had shown that ambient temperatures in the driver's compartment were hotter in the M2A3 than in the predecessor vehicle; the differential was attributed to the A3's turret vent fans and airflow patterns within the vehicles. Infantry School personnel indicated that they felt there were more issues to be identified and that there was more to the problem than airflow.

Procedure:

ARI researchers initially measured ambient temperatures inside driver compartments. This was followed by temperature measurements of various surfaces. Measurements were made in M2A3 vehicles at Fort Hood, TX, and at Fort Benning, GA. Additionally the predecessor vehicle, the M2A2 ODS (Operation Desert Storm) variant, was measured at Fort Benning. A researcher sat inside the Bradley, in the driving position, with the hatch cover closed, and took temperature readings at ten-minute intervals. In each instance, the engine was idling, but the turret power was off. The areas on which temperature measurements were recorded varied over time, as it became apparent that some areas within the compartment heat faster and to a greater extent than other areas.

Findings:

The M2A3 vehicles at Fort Hood and Fort Benning showed similar temperature patterns, despite the 15-degree external ambient temperature difference at the two locations. Two M2A3 vehicles at Fort Benning showed nearly identical temperatures and changes over time. Finally, the A3 and the ODS were found to show a similar pattern in surface temperature rise, with the A3 hotter than the A2 ODS. The cause of the temperature rise was readily apparent. The engine compartment access panel wall (between the engine and the driver) got very hot over time. The radiator-like effect produced by the engine heat transferred to other surfaces in the driver's compartment, and created an overall rise in ambient temperature. The left sides of the vehicle, away from the engine, remained relatively cool over time. The engine (right) sides of the driver's compartment increased rather rapidly, in several cases rising to a temperature of over 140° F.

Utilization of Findings:

The results of the surface temperature measurements were briefed to the Bradley TRADOC Systems Manager and the Program Manager, BFVS. As an immediate fix, one-half inch of insulation was added between the engine and the engine access panel within the driver's compartment on selected vehicles at Fort Hood. Preliminary results of additional measurements indicate that the insulation helps considerably. Further studies will be needed to determine if this abates the problem sufficiently. Systematic research may also be needed to determine effects of heat on driver performance.

BRADLEY FIGHTING VEHICLE: HEAT IN THE DRIVER'S COMPARTMENT

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Introduction

The U.S. Army Research Institute's (ARI) Infantry Forces Research Unit at Fort Benning has conducted research on the M2 Bradley Fighting Vehicle (BFV) since the inception of the Bradley program in the late 1970s. The primary focus of ARI's research has been Bradley training, and issues associated with training devices, primarily gunnery devices, although the twenty-year Bradley research program has also produced some work on human factors and engineering problems. As a consequence, a long-term institutional Bradley memory resides in ARI. Cognizant of this Bradley expertise, in early 1999, the Commanding General of the U.S. Army Infantry School and Center at Fort Benning requested that the author assist the Infantry School in informal assessment of some issues associated with the advent of the newest Bradley.

There are two versions of the Bradley – the Infantry Fighting Vehicle and the Cavalry Fighting Vehicle. The basic designs are similar and references to the BFV herein apply to both. Since its fielding in 1981, the Bradley has been upgraded to keep pace with changing demands of military conflict. It has evolved through several variants - the original M2 (also referred to as the A0, or "vanilla Bradley"), followed by the M2A1, and M2A2. Each model built upon the previous models' infrastructure, with modifications in the weapons, command and control, and targeting systems. The Army's baseline Bradley, the M2A2, was improved as a result of lessons learned during Operation Desert Storm (ODS), and is deployed worldwide as the M2A2 ODS. The M2A3 BFV, now in initial production, was designed to eliminate shortfalls in the ODS, especially in the area of digitization. However, after early testing of the new vehicle, a major area of concern was the subjective reports by Bradley crewmen that the new vehicle was too hot inside, hotter even than predecessor vehicles. And although the whole vehicle was perceived as hotter than previous Bradleys, the driver's compartment was seen as especially uncomfortable.

The author discussed the heat problem with the Bradley Training and Doctrine Command (TRADOC) Systems Manager's (TSM-B) office and with military personnel who were conducting and participating in limited user tests on the A3 vehicle. The author also attended a review of a 1999 heat test conducted by the Army Research Laboratory (ARL) at Aberdeen Proving Ground (APG). This test, discussed below, was based on concerns that the excessive temperatures in the A3 vehicle might be due to the heat generated by new computer components. Results showed that some problems might be due to new vent fans associated with computer equipment. However, after discussions with selected BFV personnel, it became apparent that other sources of heat, primarily the engine, were also causing driver discomfort.

This paper reports a preliminary effort to document the effects of the BFV's engine heat on driver compartment interior temperatures. Initial measurements of surface and ambient temperature were made at Fort Hood in September 1999, and at Fort Benning in October 1999. After the preliminary results were briefed to interested personnel, in August 2000, the engine compartment access wall was insulated in selected vehicles. Anecdotal reports from drivers indicated that the driver compartment temperatures were more moderate in insulated vehicles. Therefore, in a replication of the earlier measurements, additional surface and ambient temperature readings were made at Fort Hood, in December 2000, using an insulated vehicle. These different sets of temperature measurement, although relatively simple in their execution, provided some compelling data. Most information was gained on the A3; one set of comparison measurements was made on the M2A2 ODS. A limited literature search was conducted on temperature induced performance degradation, but further systematic research is needed, both on the effects of heat on performance, and on the newly insulated vehicles during hot seasons of the year.

Evaluation of BFV Heat Load – Aberdeen Proving Ground Chamber Tests

Newly added computer equipment in the turret of the M2A3 necessitated the addition of turret ventilation fans that are designed to engage automatically when ambient temperatures in the turret reach 85° F. The purpose of these vent fans is to protect heat-sensitive computer circuitry, but their addition

may have created an unforeseen problem. BFV personnel reported that the M2A3 vehicle, especially in the driver's compartment, seemed hotter than the M2A2. The Army Research Laboratory at Aberdeen and the BFV primary contractor, United Defense Limited Partnership (UDLP), conducted a side-by-side evaluation of the M2A3 and M2A2, utilizing an environmental simulation test chamber (Tauson, 2000; Blomquist, 1999; Cardine, 1999). In these tests, under static conditions, ambient external temperatures of 30°, 40°, 80°, 100°, and 125°F were artificially produced, and ambient internal air temperatures in the turret, driver, and squad compartment areas were measured in both vehicles. The turret fans in the M2A3 vehicle came on automatically at the higher temperatures; there are no turret vent fans in the M2A2. Tests were run both with the hull vent fans on and with the hull vent fans off.

These tests showed that temperatures inside the driver's compartment were significantly hotter in the M2A3 than in the M2A2 (up to 35° hotter), when the hull vent fans were off and turret fans were on (see Table 1). (The turret and squad areas were hot, too, but not to the same extent.) In an attempt to locate the source of the heat in the driver's compartment, smoke candles were used to determine airflow patterns in the two vehicles under varying fan use conditions. Based upon the results of the smoke candle excursion tests, the additional heat was attributed to a negative pressure condition within the driver's compartment, created by the turret fans drawing air from the engine compartment into the driver's compartment through openings in the floor (Tauson, 2000). As is shown in Table 1, operating the hull vent fans when the turret fans were on alleviated the negative pressure condition, and to a large extent, the temperature differential. Moreover, when both the hull and the turret fans were operating, driver compartment temperatures in the M2A3 were actually up to five degrees cooler than those in the M2A2 (Tauson, 2000). Tauson's data clearly indicate a problem, one that can be partially remedied by judicious use of hull vent fans.

Table 1

Temperatures in Bradley Driver Compartment Areas, Aberdeen Proving Ground

	Hull Vent Fans *Off*			Hull Vent Fans *On*		
	A2 internal temperature	A3 internal temperature	Difference	A2 internal temperature	A3 internal temperature	Difference
80°F external						
Head	97.98	123.95	25.97	101.77	103.76	1.99
Hand	92.96	128.00	35.04	102.36	102.26	-0.10
Foot	90.16	124.87	34.71	100.72	101.51	0.79
100°F external						
Head	129.35	141.27	11.92	128.44	126.30	-2.14
Hand	124.10	144.95	20.85	128.67	124.30	-4.37
Foot	120.63	142.07	21.44	127.57	123.27	-4.30

Note. Adapted from Tauson, 2000.

The results of the chamber tests (Tauson, 2000) and accompanying UDLP data (Blomquist, 1999, and Cardine, 1999) were presented at Aberdeen in August 1999. However, based on their own personal experiences, and on reports from other soldiers, Infantry School military attendees remained unconvinced that the turret and hull vent fans could be the cause of all the discomfort in the A3 driver compartment. The author, an ARI research psychologist, also in attendance at the presentation, agreed to conduct a pilot experiment to try to determine other potential causes for heat.

Fort Benning and Fort Hood Surface Temperature Assessments, September and October 1999: Overview of Procedures

The Aberdeen chamber tests concentrated on the effects of extreme environmental temperatures on ambient air temperatures in the driver, crew, and troop compartments of the two BFVs. Their primary focus was upon the airflow created by the ventilation systems of the vehicles under hot environmental conditions, and once this was discovered, how the apparently hotter conditions within the driver's compartment of the M2A3 might be resolved. In the present investigation, ARI researchers performed a comparative assessment of ambient and <u>surface</u> temperatures in the driver compartment of the M2A2 ODS and M2A3 Bradleys. The ARI data collections were iterative in nature; each set of measurements lead to another. First, an A3 was measured. Then an A2 ODS was measured, and finally other A3s were measured. The A3 and ODS results were compared, and the A3s were compared.

Comparisons of vehicle temperatures at Fort Hood and Fort Benning produced a number of findings. Some of them are fairly obvious or intuitive; others are more surprising. Basically, however, the data show that there were no real differences between M2A3 vehicles, either between the A3s at Fort Benning or between them and the M2A3 at Fort Hood. The patterns of temperature rise were consistent with start temperatures, their rise was parallel and the only (minor) differences appeared a function of the external temperature (solar load). The M2A3 and M2A2 ODS comparisons showed that the <u>pattern</u> of temperature rise was similar between the two vehicles, the only real difference being the actual temperatures. Both the A3 and the ODS showed hot temperatures (ambient and surface) in the driver's compartment; the only difference being that the A3's were more extreme.

The following sections describe the procedures followed. The first measurements at Fort Hood focused on interior ambient temperature. The next, several weeks later, focused on A3 surface temperatures, and defined some specific measurement areas. The Benning trials repeated the latter Fort Hood measures, and compared the two different types of vehicles. The final test, conducted in December 2000, replicated the earlier tests, on an A3 that had been modified by the addition of a half-inch thick piece of insulation in the wall panel between the driver and the engine.

Initial Measurements – Fort Hood

In the early stages of the investigation, the author conducted baseline temperature evaluations of several M2A3 vehicles at Fort Hood, TX, under natural environmental and operational conditions. All temperature measurements were conducted with the BFV engine idling while parked in open terrain with turret power off and <u>all</u> ventilation fans off. (Since the turret power was off, neither the computers nor the turret vent fans were on.) Therefore, any temperature differential recorded could not be attributed to ventilation fan issues or computer component temperatures. Driver's compartment hatches were closed and the troop compartment ramps were down (open) in all vehicles tested.

The author sat in the driver's seat, facing forward, and measured the ambient interior air temperature at 10-minute intervals using a Radio Shack® digital thermometer that was suspended from the steering yoke at the approximate midline of the driver's compartment. In the course of obtaining these initial exploratory measurements, it became apparent that as the vehicle idled, the right (engine wall) side of the vehicle's driver compartment interior gradually began to feel warmer than the left side. Thus, during the process of assessing ambient temperature, another potential contributing source of heat stress became obvious: the engine side of the compartment seemed much hotter than the non-engine side.

Surface Temperatures – Fort Hood M2A3 Vehicle

This initial assessment was followed up with additional temperature measurements. During these investigations, in addition to measuring internal ambient air temperatures, the author utilized a Raynger® ST non-contact laser thermometer to assess surface temperatures within the vehicle. After a series of trial and error measurements, a comprehensive set of measurement points was established to capture ambient <u>and</u> surface temperatures throughout the driver's compartment of the vehicle.

Figures 1 – 6 depict the locations where surface temperature measurements were made. The surface measurement points can be categorized into three broadly defined areas: the left, the center, and the right sides of the interior of the driver's compartment. The left side (of a forward-facing driver) is the area adjacent to the exterior wall. It includes the heater controls and the driver's navigation display unit (A3 only) (Figure 1). The center area includes what is directly in front of the driver - the driver's steering yoke, and the foot pedal areas (Figure 2). The right side is the area adjacent to the engine wall. This side can be further divided into the front (gearshift, engine caution signs) (Figures 3 and 4) and rear (two engine access panels) (Figures 5 and 6). The forward of the two engine access panels has a large sign with operations instructions printed on it.

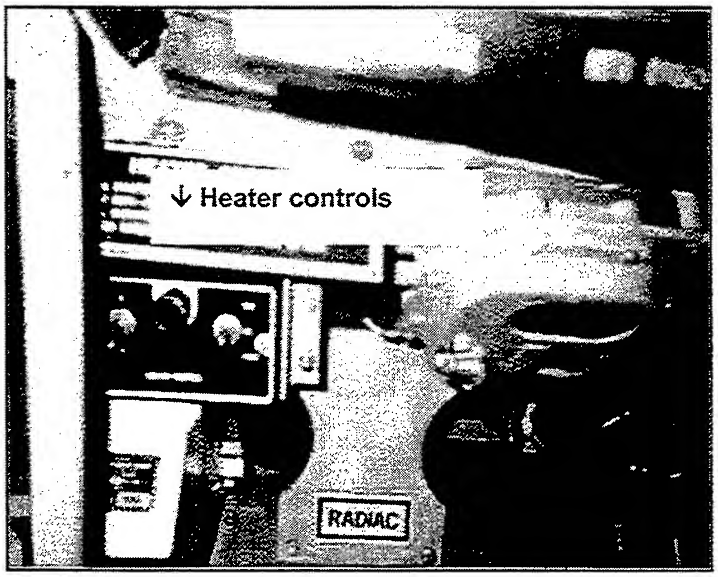

Figure 1. Left side – heater controls

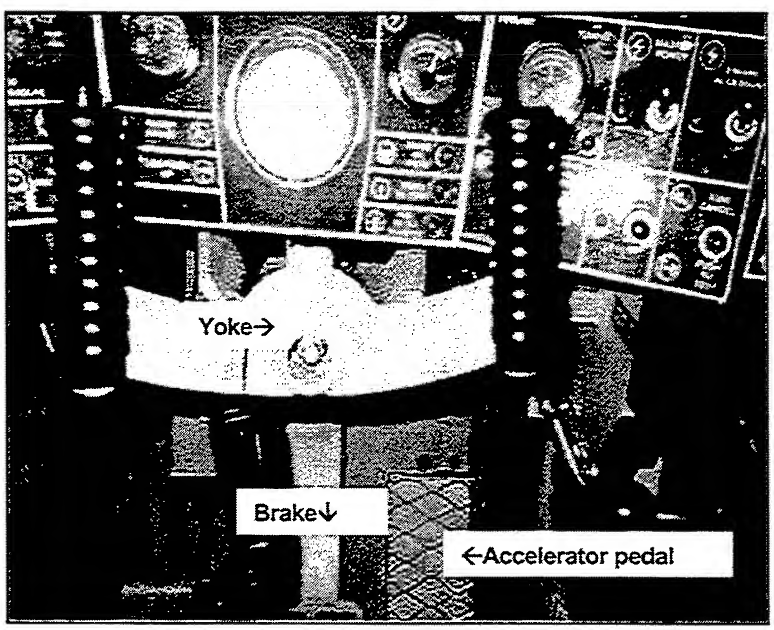

Figure 2. Center – steering yoke, foot pedals

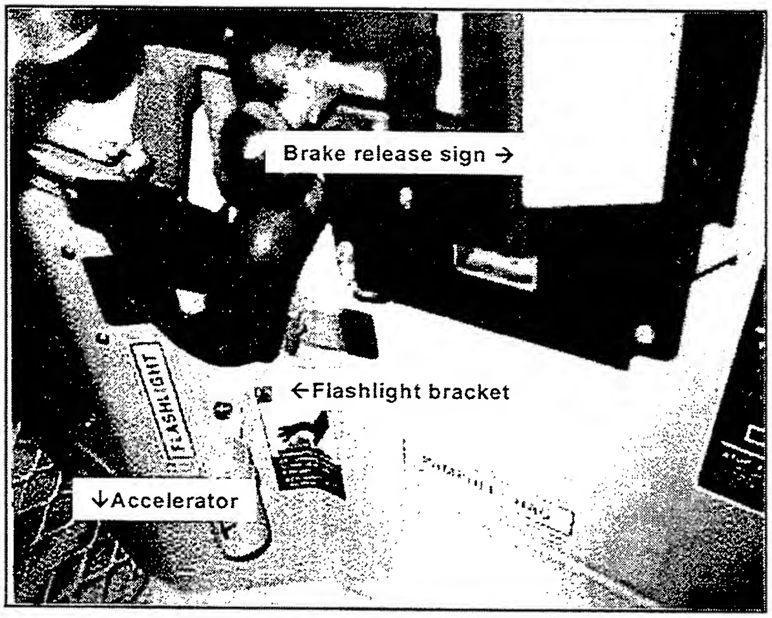

Figure 3. Right side (forward, low) – flashlight bracket

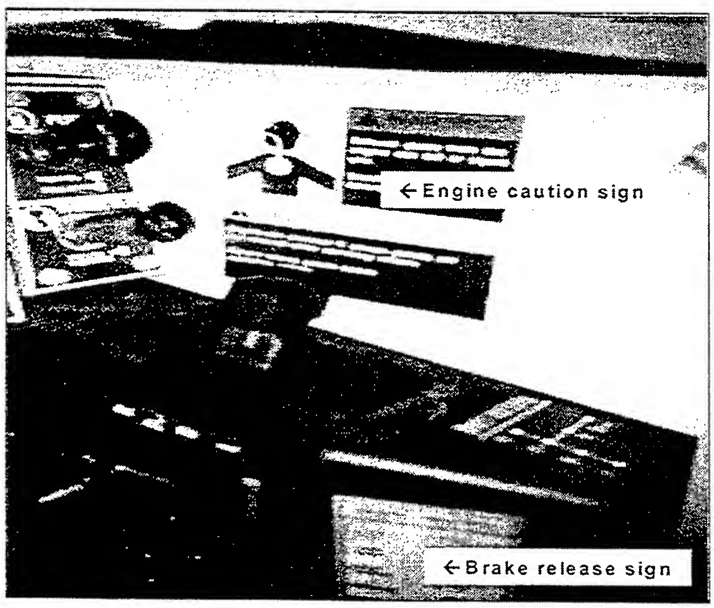

Figure 4. Right side (forward, high) – engine caution sign, brake release sign

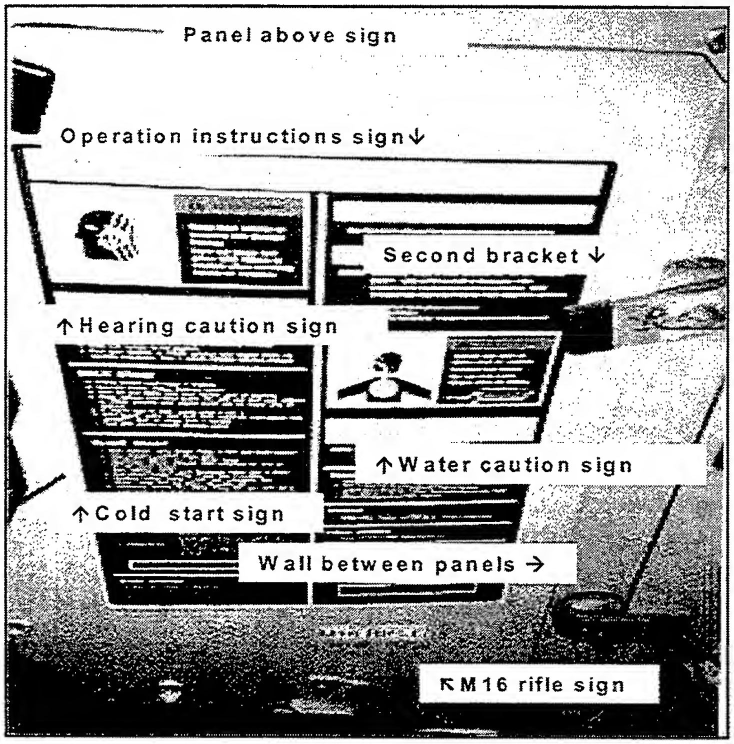

Figure 5. Right side (front) – forward engine access panel, with operation instruction sign

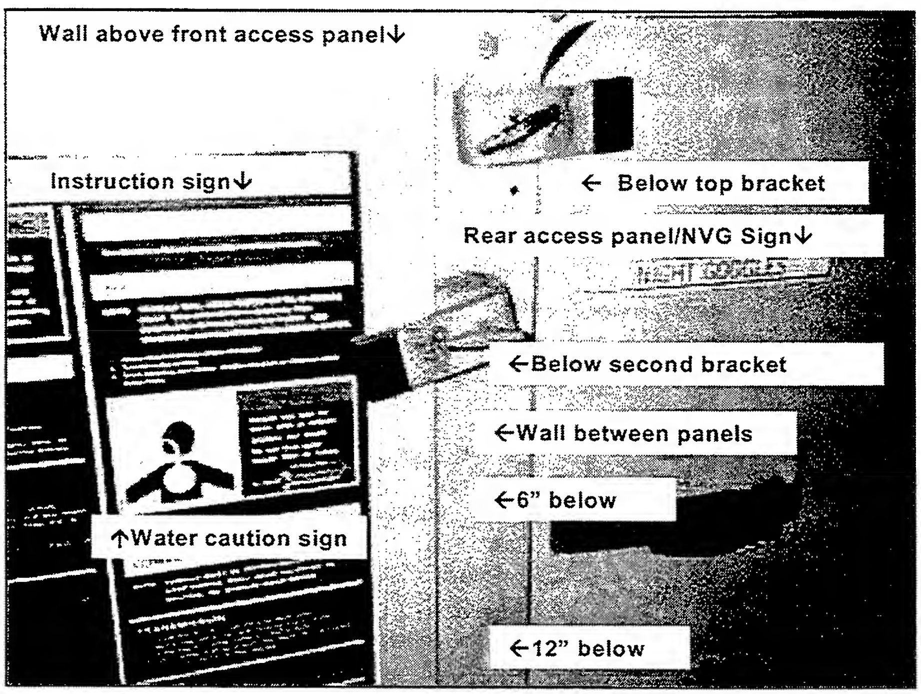

Figure 6. Right side (rear) – rear engine access panel, brackets, wall between access panels

The M2A3 vehicle was parked in a Fort Hood motor pool, engine running, with vent fans and turret power off. The author sat in the driver's compartment, in the normal driving position, with the hatch closed, and made measurements with the Raynger® thermometer at ten-minute intervals throughout the day. Temperature readings were made in an eight to ten minute circuit. After one point was measured and its temperature recorded, the next location was measured. When the final point was measured, the process began again, measuring locations in the same order each time. This process continued throughout the time period, except during an enforced break at midday when the vehicle was shut down. This did not appear to affect the pattern of the temperatures. As the day wore on, new locations were added to the list of measured places as additional heat differentials were discovered. By the end of the day, over 20 points were being evaluated and the changes in surface temperatures noted.

Table 2 shows the change in surface temperature over time within one single M2A3 vehicle at Fort Hood on a moderate day, with external temperature approximately 80°F. As noted, the vehicle was in a motor pool, with the engine idling, turret power off, and hull and turret vent fans off. The driver's hatch was closed. The author sat in the driver's seat and began measurements just after the vehicle was turned on. Measurement began at 0915 and ended after 1430, except for areas marked with an asterisk where initial readings occurred at varying times throughout the day. (For those areas, the change in temperature from the initial to the final reading is artificially small.)

The interior ambient temperature thermometer remained suspended from the driver's steering yoke and the temperature, recorded throughout the day, rose just over 20 degrees. Several locations within the three measured areas reflected that rise. Portions of the left side of the vehicle (heater controls), center (e.g. steering yoke, accelerator, and brake release sign) and the front part of the right side (engine caution, brake release, wall above the access panels) rose in temperature somewhat in parallel with the interior ambient temperature.

In other areas on the right side, however, the rise in temperature was very large, especially in areas adjacent to the engine access panels. Based on these initial and preliminary measurements, it was apparent that the M2A3's driver compartment was reaching a warm interior ambient temperature (100°F) and that some areas had surface temperatures in excess of 140°F. The next logical step was to compare these data to data collected from other vehicles.

The next phase in the heat measurement process consisted of collection of measurements from an M2A2 ODS vehicle and additional M2A3 vehicles. One reason for these supplementary measurements was to determine if the pattern of heat increase in the driver compartment over time was limited to the Fort Hood environment or to the A3 vehicle. Another reason was to see what variance might occur between different vehicles on the same day.

Table 2

M2A3 Temperature Measurements at Fort Hood, TX (Sept. 17, 1999)

Location	First Reading (°)	Final Reading(°)	Change
Interior Ambient Temperature	79.4	100.5	21.1
Heater Controls	75.8	99.6	23.8
Waypoint Screen *	90.6	108.6	18.0
Steering Yoke	77.2	103.3	26.1
Inside of Hatch Cover *	100.7	111.4	10.4
Accelerator Pedal	81.9	102.8	20.9
Floor by Brake Pedal	83.5	103.0	19.5
Flashlight Rack *	110.5	123.1	12.6
Engine Caution Sign	80.4	149.5	69.1
Brake Release Sign	79.4	109.1	29.7
Wall Above Front Engine Access Panel *	109.5	136.5	27.0
Hearing Caution Sign	81.4	132.7	51.3
Water Caution Sign	81.4	125.1	43.7
Cold Start Sign	80.8	128.5	47.7
M 16 Rifle Sign	80.8	113.3	32.5
Wall Between Access Panels *	99.0	150.1	51.1
Below Top Bracket *	101.7	150.8	49.1
Night Goggles Sign	80.0	122.4	42.4
Below Second Bracket *	109.3	152.5	43.2
6" Below Second Bracket *	112.9	148.2	35.3
12" Below Second Bracket *	111.6	137.8	26.2

Note. * denotes readings added after the original start time.

Surface Temperatures - Fort Benning M2A2 ODS Vehicle

The procedures used with the A2 ODS vehicle at Fort Benning were the same as had been used with the A3 at Fort Hood. Again, the author collected temperature measurements at 10-minute intervals for the entire test day except for an approximate one-hour midday break. During this break, the test vehicle continued idling with the driver hatch closed and the ramp down.

Table 3 shows measurements from the M2A2 ODS vehicle. The ODS vehicle does not have a Waypoint Screen and the Driver's Compass Display is new in the A3. There was no comparable location in the A2 ODS for this measurement. The A2 ODS rear engine access panel has a label for Gunner's Spare Parts, where the A3 panel has a bracket for storage of Night Vision Goggles. Since the locations are the same on the panel, this location was retained for the ODS measurements.

Table 3 shows a pattern similar to that found in the Fort Hood data collection. In the ODS vehicle the interior ambient temperature rose just over twenty degrees over the course of the day; the heater controls (left side) and center measurement areas rose similarly to each other, and to about the same extent as the interior ambient temperature. The right side of the vehicle again showed a large increase in temperature over the course of the day. As with the A3, the front part of the right side of the A2 ODS was cooler than the rear part, with the excessive surface heat in the area between the engine access panels.

The overall change from the initial to the final measurement was at some times greater in the ODS than in the A3, possibly because the initial starting ambient temperature was lower at Fort Benning than at Fort Hood. However, the specific temperatures in the hot areas were lower in the A2 ODS vehicle than they were in the A3 vehicle.

Table 3

M2A2 ODS Temperature Measurements at Fort Benning, GA (Oct. 6, 1999)

Location	First Reading (°)	Final Reading(°)	Change
Interior Ambient Temperature	63.3	85.7	22.4
Heater Controls	59.9	85.6	25.7
Waypoint Screen	NA	NA	NA
Steering Yoke	62.1	88.0	25.9
Inside of Hatch Cover	55.5	96.7	41.2
Accelerator Pedal	61.6	89.9	28.3
Floor by Brake Pedal	58.1	81.7	23.6
Flashlight Rack	61.0	108.6	47.6
Engine Caution Sign	59.2	121.9	62.7
Brake Release Sign	60.0	92.9	32.9
Wall Above Front Engine Access Panel	59.5	105.8	46.3
Hearing Caution Sign	61.6	112.2	50.6
Water Caution Sign	61.5	105.7	44.2
Cold Start Sign	62.1	110.9	48.8
M 16 Rifle Sign	59.8	95.0	35.2
Wall Between Access Panels	62.6	122.7	60.1
Below Top Bracket	61.2	112.5	51.3
Night Goggles Sign/Spare Parts	59.2	92.4	33.2
Below Second Bracket	62.3	120.7	58.4
6" Below Second Bracket	63.4	123.7	60.3
12" Below Second Bracket	64.0	123.1	59.1

Note. The M2A2 ODS has no Waypoint Screen. The Gunner's Spare Parts sign is in the same location in the ODS as the Night Goggles sign is in the A3.

Surface Temperatures - Fort Benning M2A3 Comparisons

The next set of measurements was made with two side-by-side M2A3 vehicles to assess between vehicle consistencies. The procedures were identical to those used in previous measurements. An anomaly in measurement locations became apparent at the end of the test day, however, when the two researchers exited their vehicles. One of the researchers had erroneously measured temperatures directly on the engine access panel brackets, rather than below them as was intended. This error led to a considerable difference in reported temperatures between the vehicles in these areas only (see Table 4), since the brackets themselves are of a more heat-resistant metal than the steel panel to which they are attached. With the exception of the "top bracket" and "second bracket" locations, however, the temperatures within the two vehicles tested were nearly identical to each other.

Table 4

M2A3 Temperature Comparisons at Fort Benning, GA (Oct. 18, 1999)

Location	A3 #1 – First Reading (°)	A3 #1 - Final Reading (°)	Change	A3 #2 – First Reading (°)	A3 #2 - Final Reading (°)	Change
Interior Ambient Temperature	70.7	90.5	19.8	68.2	89.0	20.8
Heater Controls	67.2	86.2	19.0	66.5	85.8	19.3
Waypoint Screen	69.6	86.7	17.1	66.8	86.3	19.5
Steering Yoke	68.0	92.4	24.4	67.7	91.5	23.8
Inside of Hatch Cover	65.4	97.5	32.1	65.1	91.7	26.6
Accelerator Pedal	67.6	91.2	23.6	67.1	93.3	26.2
Floor by Brake Pedal	67.8	86.2	18.4	68.7	85.4	16.7
Flashlight Rack	68.9	118.3	49.4	67.6	118.3	50.7
Engine Caution Sign	68.2	132.1	63.9	67.5	128.5	61.0
Brake Release Sign	68.5	98.6	30.1	68.0	98.6	30.6
Wall Above Front Engine Access Panel	67.8	119.8	52.0	66.9	119.5	52.6
Hearing Caution Sign	68.5	124.6	56.1	67.5	124.1	56.6
Water Caution Sign	69.2	115.8	46.6	67.2	115.4	48.2
Cold Start Sign	70.1	124.4	54.3	68.5	121.8	53.3
M 16 Rifle Sign	67.8	101.9	34.1	66.1	102.2	36.1
Wall Between Access Panels	71.3	139.8	68.5	68.9	145.5	76.6
Below Top Bracket *	69.1	118.4	49.3	66.7	140.3	73.6
Night Goggles Sign	68.4	115.8	47.4	66.3	117.6	51.3
Below Second Bracket *	68.8	119	50.2	67.4	145.2	77.8
6" Below Second Bracket	72.0	143.8	71.8	68.6	145.8	77.2
12" Below Second Bracket	72.6	139.8	67.2	69.3	141.8	76.6

* Locations in which the two researchers varied aim points.

Table 4 shows the results of comparing two M2A3s in a side-by-side evaluation. As before at Fort Hood, the two M2A3s showed comparable rise in ambient temperature, paralleled by the elevation in the left and center areas. The rise in temperature in the right side, especially in the engine panel area, was again very noticeable.

Summary of 1999 Results

Comparisons of M2A3 vehicles and the M2A2 ODS vehicle produced a number of findings. First, there are no real differences from one A3 to another. The three showed temperature increases over time, and the pattern of temperature rise was the same over all vehicles. The ODS vehicle showed a similar rise and pattern over time. The difference between the two was that in some specific areas, the absolute temperatures in the A3 were higher than in the ODS vehicles. However, inspection of the data shows that both vehicles are probably too hot.

For human heat and humidity tolerances, the standard for environmental temperature measurement is wet bulb globe temperature (WBGT). Developed in 1957, WBGT was devised specifically for the U.S. Armed Forces to establish a consistent standard for testing human heat endurance (Kobrick & Johnson, 1991). Most calculations of human performance in heat and humidity are performed with WBGT, and it is recognized as the standard when investigating human responses to heat stress. As a part of the chamber test, Tauson (2000) extrapolated the maximum number of hours that BFV personnel could comfortably operate. At WBGT temperatures of 80°, the heat load in the M2A3 driver compartment (with hull vent fans off) would result in a maximum safe exposure time of approximately 1.5 hours. The maximum safe exposure limit exceeds 6 hours when hull vent fans are on. At 100°, maximum exposure times in both the M2A2 and M2A3 driver's compartments would be 1.5 hours or less, regardless of hull vent fan use (Tauson, 2000). Therefore, when environmental temperatures approach or exceed 100°, effective operations may be severely limited in both vehicles.

Table 5 shows the comparative changes in temperature over time, compiled from the preceding three tables. For example, over the course of the day, the surface temperature of the steering yoke rose between 23.8 and 26.1 degrees for the four vehicles, from the first measurement to the last. A similar pattern was found for the accelerator pedal area where temperatures rose between 20.9 and 28.3 degrees over the day. On the engine caution sign, the temperatures rose between 61.0 and 69.1 degrees, similar for the four vehicles, but much larger than the rise in other areas. Areas with asterisks represent those in which the original measurements varied in some way from the others, in length of time from initial to final readings or, in one of the Fort Benning A3s, in actual location. These asterisked areas show artificially low change values.

The comparisons of vehicles show very few differences between M2A3 vehicles, either between the A3s at Fort Benning or between them and the M2A3 at Fort Hood. The patterns of temperature rise were consistent with start temperatures, their rise was parallel and the actual difference appeared to be a function of the external temperature (solar load). The M2A3 and M2A2 ODS comparisons showed that the pattern of temperature rise was similar between the two vehicles, the only real difference being the absolute temperatures in some areas. This is reflected in Table 6 that shows the maximum temperature recorded in each area in each vehicle.

Table 5

Changes (in Numbers of Degrees) from Initial to Final Measurements over a Day (Four Vehicles)

Location	Fort Hood A3 Change	Fort Benning ODS Change	Fort Benning A3 #1 Change	Fort Benning A3 #2 Change
Interior Ambient Temperature	21.1	22.4	19.8	20.8
Heater Controls	23.8	25.7	19.0	19.3
Waypoint Screen	18.0	NA	17.1	19.5
Steering Yoke	26.1	25.9	24.4	23.8
Inside of Hatch Cover *	10.4	41.2	32.1	26.6
Accelerator Pedal	20.9	28.3	23.6	26.2
Floor by Brake Pedal	19.5	23.6	18.4	16.7
Flashlight Rack *	12.6	47.6	49.4	50.7
Engine Caution Sign	69.1	62.7	63.9	61.0
Brake Release Sign	29.7	32.9	30.1	30.6
Wall Above Engine Access Panel *	27.0	46.3	52.0	52.6
Hearing Caution Sign	51.3	50.6	56.1	56.6
Water Caution Sign	43.7	44.2	46.6	48.2
Cold Start Sign	47.7	48.8	54.3	53.3
M 16 Rifle Sign	32.5	35.2	34.1	36.1
Wall Between Access Panels*	51.1	60.1	68.5	76.6
Below Top Bracket *	49.1	51.3	49.3	72.6
Night Goggles Sign	42.2	33.2	47.4	51.3
Below Second Bracket *	43.2	58.4	50.2	77.8
6” Below Second Bracket*	35.3	60.3	71.8	77.2
12” Below Second Bracket*	26.2	59.1	67.2	76.6

* Measurement anomalies, see Tables 2 - 4.

Table 6

Highest Recorded Temperatures (°F) in Four Vehicles

Location	Fort Hood A3	Fort Benning ODS	Fort Benning A3 #1	Fort Benning A3 #2
Interior Ambient Temperature	100.5	85.7	90.5	89.0
Heater Controls	99.6	85.6	86.2	85.8
Waypoint Screen	108.6	NA	86.7	86.3
Steering Yoke	103.3	88.0	92.4	91.5
Inside of Hatch Cover	111.4	96.7	97.5	91.7
Accelerator Pedal	102.8	89.9	91.2	93.3
Floor by Brake Pedal	103.0	81.7	86.2	85.4
Flashlight Rack	123.1	108.6	118.3	118.3
Engine Caution Sign	149.5	121.9	132.1	128.5
Brake Release Sign	109.1	92.9	98.6	98.6
Wall Above Engine Access Panel	136.5	105.8	119.8	119.5
Hearing Caution Sign	132.7	112.2	124.6	124.1
Water Caution Sign	125.1	105.7	115.8	115.4
Cold Start Sign	128.5	110.9	124.4	121.8
M 16 Rifle Sign	113.3	95.0	101.9	102.2
Wall Between Access Panels	150.1	122.7	139.8	145.5
Below Top Bracket *	150.8	112.5	118.4	140.3
Night Goggles Sign Area	122.4	92.4	115.8	117.6
Below Second Bracket *	152.5	120.7	119.0	145.2
6" Below Second Bracket	148.2	123.7	143.8	145.8
12" Below Second Bracket	137.8	123.1	139.8	141.8

* Measurement anomalies, see Tables 2 - 4.

Discussion of Results

External Heat Factors

First, and not surprisingly, when external environmental temperatures changed, interior ambient temperatures in the vehicles also changed. For example, in the Fort Hood assessment, initial temperature measurements inside the M2A3 reflected the relatively warm external environmental temperature of 78° F. In comparison, the Fort Benning ODS assessment began with environmental temperatures of 65° F. In each case the external, outside, temperature rose about 15 degrees throughout the day. At the end of the measurements, interior ambient temperatures had increased at roughly the

same rate in the two vehicles, so that the ratio of temperatures remained commensurate. The Fort Hood M2A3 final interior ambient temperature was 100.5°F, while the Fort Benning M2A2 ODS ending interior ambient temperature was 85.7°F, each rising approximately 20 degrees from its earliest measured temperature. Similarly the internal ambient temperatures in the A3 Vehicles at Fort Benning rose approximately 20 degrees over the course of a day from their start point of about 68°F. Additionally, the environmental (external ambient) temperatures similarly affected surface temperatures within these two vehicles. For example, the steering yoke temperatures in the Fort Benning M2A3 vehicle #1 ranged from 68° to 92.4°F (+24.4°), while the Fort Hood M2A3 steering yoke ranged from 77.2° to 103.3°F (+26.1°), again reflecting the relationship between environmental and interior surface temperatures.

Within Vehicle Changes

Early on in the measurements, even during the initial explorations at Fort Hood, it became apparent that different areas within the vehicles showed different surface temperatures regardless of ambient temperatures. The disparity increased as the day wore on. As noted earlier, the temperature measurements were categorized into left, center and right sides, and within the right side, front and back. Tables 2, 3, and 4 show the rise in surface temperatures. As the ambient temperature rose, the surface temperatures of the left and center areas rose comparably. The entire right side, especially the area between the two engine access panels, heated at a much faster rate and to a much higher degree than any other areas measured. The absolute temperatures in every area rose, but the areas adjacent to the engine rose at a higher rate, and to a higher temperature than anywhere else. Additionally, within the driver's compartment, every engine-adjacent surface measured was hotter (in degrees) in the A3 than in the ODS. These differences did not manifest in other areas of the two vehicles, e.g., the heater controls, steering yoke, brake pedal. The reason for the differences between the A3 and the ODS engine areas is unknown, and although beyond the purview of this report, bears investigation.

Effects of Heat on Performance

The effects of extreme thermal environments on human cognitive and physical performance have been given considerable attention in the medical, psychological, and human factors literature, with mixed results (Kobrick & Fine, 1983; Kobrick & Johnson, 1991; Ramsey, 1995; Tauson & Doss, 1997). In the military environment, where erroneous decision-making can produce potentially serious results, understanding the effects of thermal stress on human performance is essential. Military personnel operate complex and expensive equipment, often utilizing weapons systems that require rapid and accurate discriminative decision-making skills. Therefore, any factor that might adversely affect the ability to operate effectively requires attention.

The high temperatures encountered in military aircraft and armored vehicles are well documented. A review of the heat stress literature (Kobrick & Fine, 1983; Ramsey, 1995; Tauson & Doss, 1997) reported varying levels of cognitive impairment related to thermal stress, depending upon the type of task assessed. There are reports of some cognitive and perceptual impairment even at levels of thermal stress that are not typically considered extreme, e.g., 90°F. The types of tasks that were most affected were those involving vigilance, tracking, reaction time, and visual acuity (Ramsey, 1995; Kobrick & Johnson, 1991; Azer, McNall, and Leung, 1972), and complex tasks such as operating a vehicle (Wyon, Wyon, and Norin, 1996). On the battlefield even a slight impairment in any of these areas of performance may reduce survivability.

According to Tauson and Doss (1997), the 1989 Department of Defense Military Standard (MIL-STD) 1472D, and the 1980 Departments of the Army, Navy, and Air Force Technical Bulletin – Medical (TB - MED), Number 507, set a criterion that crew compartment temperatures should not exceed 85°F for 12-hour exposure times. Recommended exposure times decrease rapidly as temperature increases or when personnel are wearing protective garments. Tauson and Doss (1997) suggested that, as a rule of thumb, use of mission oriented protective posture, level four (MOPP-IV) gear adds approximately 10 degrees to the ambient temperature, reducing soldiers' ability to compensate for thermal stress through evaporative cooling (sweat).

When soldiers were asked to perform various tasks while wearing MOPP-IV garments under heat stress, Kobrick, Johnson, and McMenemy (1988) reported significant performance decrements. Performance was measured at temperatures of 55°F and again at 95°F. Reaction time increased, and rifle marksmanship was 57% less accurate under the heat conditions, and verbal reasoning tasks were performed with 58% less accuracy. Taylor and Orlansky (1993) reported that performance decrements were significant when military personnel wore chemical warfare clothing even when heat stress was not a factor. The combination of protective clothing and an enclosed vehicle may produce extreme thermal stress.

It has been repeatedly demonstrated that heat exposure negatively impacts performance of a number of tasks to varying extents. In addition to the cumulative cognitive blunting effects of heat exposure (Kobrick & Johnson, 1991), research with Army aircraft and armor crews has demonstrated some impairment in decision-making, judgment, and mood states, which is exacerbated under combined conditions of heat stress and deployment of MOPP-IV gear (Tharion, Rauch, Munro, Lussier, Banderet, and Shukitt, 1986). It is, therefore, important to address the issue any time personnel are exposed to heat stress.

The Effect of Engine Heat

Overall, temperatures were noticeably warmer on the right side of the driver's compartment than on the left side, apparently due to thermal transference from the engine compartment to the adjacent wall in the driver's compartment. For example, in the early morning, the entire interior of the vehicle was cool. The author was initially subjectively unaware of any temperature differences between the right and left side of the driver's compartment. As the day progressed, however, the left side of the driver's compartment initially remained cool, while the right side temperature increased relatively quickly. There was a consistently noticeable difference in temperature from the left to right side of the driver's compartment as the day progressed, regardless of interior ambient air temperatures. Nevertheless, the entire driver's compartment eventually became uncomfortably hot in the afternoon hours. This phenomenon was evident in both the M2A2 ODS and M2A3 to some extent, but the level of thermal transference (radiant heat) appeared to be higher in the M2A3. This is consistent with anecdotal evidence provided by Bradley personnel who have indicated that while both BFV drivers' compartments are hot, the M2A3 is hotter.

The clearly defined area of the most pronounced temperature variance (engine adjacent areas of the M2A3, and to a much lesser extent, the A2) suggests that a primary source of the variance is radiant transfer of engine heat into the driver's compartment. Turret and hull vent fans may be contributory heat sources, or may help distribute it more rapidly, but it is unreasonable to assume that the temperature levels in the driver's compartment could be produced by electronics in the turret. This is particularly unlikely given that temperatures were cooler on the left (non-engine adjacent side) than on the right (engine adjacent). Additionally, of course, during these measurements, the turret power was off, and none of the vent fans were on.

Possible Temperature Plateaus

Although the relationship between exterior and interior temperatures was seen in nearly every area measured in the M2A3 BFV, it is important to note that a maximum temperature plateau appeared to exist. Demonstrating this, the temperature of the Fort Hood vehicle's engine adjacent panels and brackets reached a maximum of 153° (with a maximum interior ambient temperature of 100.5°). The Fort Benning counterparts reached a maximum of 150.8° (with a maximum interior ambient temperature of 90°). The rate of temperature increase appeared to be slowing considerably as these measurements were taken, but further investigation will be necessary to determine the precise maximum temperature plateau and the exact nature of the interaction between environmental temperature and interior surface temperatures of the M2A3. If there is an upper limit to the temperature rise, the results of "fixes" would seem easily measured.

Impact of Heat Findings

The operational significance of the temperature differences between the M2A2 ODS and M2A3 BFV is not immediately apparent, but prior research reported herein (Ramsey, 1995; Kobrick and Johnson, 1991), would suggest that degradation of driver readiness and operational effectiveness is a potential result. Recorded ambient interior air temperatures of between 85°F and 100°F in the M2A2 ODS and M2A3 respectively, may reveal an inherent difficulty in achieving practical compliance with previously mentioned MIL-STD-1472D and TB-MED 507 guidelines (Tauson and Doss, 1997). Additionally, the surface temperature measurements were made on days when the exterior ambient temperatures were relatively low. The more typically high temperatures found at Fort Hood and Fort Benning and in other operational climates might exacerbate these temperature problems. Further research is warranted.

Possible Engineering Solutions

As a part of the Aberdeen discussions in August of 1999, several means were suggested of remedying the apparent A3 heat problems beyond the requirement that personnel in the A3 turn on all hull and vent fans whenever they are in the vehicle. There are advantages and disadvantages to the various potential engineering "fixes" that might be employed to reduce heat load within the driver's compartment of the BFV. The most intuitively appealing solution may be the implementation of an air-conditioning system, but this resolution may be cost-prohibitive, as well as require extensive retrofitting of presently fielded vehicles.

A second possibility is the utilization of an insulation blanket, which could be deployed as a covering over the vehicle to reduce the solar heat load in hot environments. This is a less appealing solution for several reasons, not the least of which is soldier workload. Deployment of a covering of this nature would require crews to contend with a cumbersome and unwieldy blanket-like shield. This blanket might interfere with some equipment, to include the TOW missile launcher, and might result in the battlefield being littered with discarded solar shield blankets. Another potential drawback would depend upon the specific design developed, but a solar shield might have the possibly unforeseen effect of trapping heat from internal sources, such as the engine.

A third and far less expensive solution, and one supported by the data described, would be the addition of a layer of insulation between the engine and driver's compartment. This solution would seem to be indicated based upon the evidence reported herein, which clearly suggests that a major source of heat in the BFV driver's compartment is radiant heat transfer from the engine. This solution would not impact soldier workload, but would reduce heat transfer. It applies a specific solution to a specifically identified problem area, which would seem to be the most cost-effective approach to any engineering problem.

Measurements of Heat in the BFV Driver Compartment: December, 2000

After the results of the previously described measurements were briefed to the TSM Bradley, and provided to the Project Manager, Bradley, the UDLP contractor attempted the third solution as described above. In August 2000, sixteen vehicles belonging to the first unit equipped at Fort Hood were fitted with a half-inch thick layer of insulation behind the front and rear access panels, and behind the wall between the panels (see Figure 6). This insulation was clearly intended to dampen the engine heat, and protect the driver from the radiator-like access panels. Subjective reports from drivers of this unit who used the newly insulated vehicles in their initial operator test and evaluation were very positive. Drivers who had been in A3s both without and with the new insulation said they were more comfortable.

The Bradley TSM Office at Fort Benning requested that the author repeat the earlier driver compartment measurements, using an insulated vehicle, to see if the heat problem had been eliminated. Due to the unit's test commitments, the author was unable to perform these tests until the weather had turned cool, in December. However since the exterior ambient temperature is of minimal impact, testing on a day with starting temperature of approximately 55 degrees was deemed acceptable.

Procedures followed in obtaining the new set of measures were identical to those performed earlier, with a few insignificant changes. Since the unit was preparing for gunnery, all of the insulated vehicles were on the range waiting to fire. In the morning, one vehicle, temporarily deadlined because of communications failure, was used for testing. Measurements started at 0920, but had to be stopped at 1035 when the problem was fixed, and the crew needed to proceed to the firing line. The author felt, however, that sufficient data had been obtained from that vehicle. In the afternoon a limited amount of data was collected on a second vehicle, one that was temporarily at the ammunition supply point. Again, when the crew was ready to proceed to the firing line, data collection had to be stopped.

As before, the author sat in the driver compartment and performed a round robin type of measurement, using the same Raynger™ thermometer to measure surface temperatures, and the Radio Shack ambient temperature thermometers to measure the interior ambient temperature. The hatch cover was closed, the engine was idling, and the troop compartment door was open. The exterior (outside) morning temperature was approximately 55 degrees; by afternoon on a cloudy day it had risen barely 20 degrees.

The results of these new measurements are shown at Table 7. With respect to the left side of the vehicle, and the center, the pattern described previously held. As the day wore on, internal ambient temperature rose nearly twenty degrees, and the components located on the left and in the center rose comparably. The pattern of measurements on the right side, however, was distinctly different from the earlier measurements.

The primary area of concern in previous measurements had been the front and rear access panels, and the wall in between them. In the insulated vehicles, the absolute temperature levels on the front access panel tended to rise between 31 and 37 degrees over time, lower than the 40 to 50 degree rise reported earlier. The rear panel's night vision goggles sign rose only 31 degrees, rather than the 40 to 50 degree rise earlier. The most noticeable change was in the wall between the two panels. In the insulated vehicles, the change from first to last measurement was between 39 and 44 degrees, comparable to the change on the panels. This is in contrast to the 70-degree changes in these areas in the previous measurements. (Appendix A shows summary data for all change measurements, from Fort Hood, Fort Benning and again at Fort Hood.)

For comparison purposes, selected change measurements for two vehicles are shown at Table 8. These include the areas of the engine access panels, and the wall between them, those areas shown hottest in the original measurements. Simple inspection shows the difference in the pattern of temperature rise between the insulated and non-insulated vehicles.

Table 7

M2A3 Temperature Measurements at Fort Hood, TX (Dec. 4, 2000)

Location	First Reading (°)	Final Reading (°)	Change
Interior Ambient Temperature	52.6	71.3	18.7
Heater Controls	45.7	60.5	14.9
Waypoint Screen	51.6	70.5	18.9
Steering Yoke	47.7	72.5	24.8
Inside of Hatch Cover	42.5	63.0	20.5
Accelerator Pedal	47.2	70.7	23.5
Floor by Brake Pedal	46.3	71.5	25.2
Flashlight Rack	56.5	99.3	42.8
Engine Caution Sign	63.2	119.5	56.3
Brake Release Sign	50.0	79.6	29.6
Wall Above Front Engine Access Panel	55.9	96.8	40.9
Hearing Caution Sign	51.4	88.5	37.1
Water Caution Sign	49.3	81.2	31.9
Cold Start Sign	50.5	84.1	33.6
M 16 Rifle Sign	44.5	63.9	19.4
Below Top Bracket	51.8	95.8	44.0
Night Goggles Sign	48.6	79.9	31.3
Below Second Bracket	51.2	94.0	42.8
6” Below Second Bracket	49.9	92.2	42.3
12” Below Second Bracket	49.2	88.3	39.0

In each instance, the earlier measurement, from the non-insulated A3, showed a higher number of degrees change in surface temperature over time than did the insulated A3. The differences on the panels themselves (signs) are not high, and might possibly be attributed to the exterior (outside) cool temperatures in December. The difference between the two vehicles on the engine wall between the two access panels, however, is quite striking. In the un-insulated vehicle, the four key measures changed between 73.6 and 77.8 degrees over the course of the day; in the insulated vehicle the rise was between 29.6 and 37.6 degrees. Although there may be some effect due to exterior ambient temperature, it seems clear that the insulation of the engine access panels has made a difference. It is interesting to note that the Engine Caution Sign at 119.5 has the highest surface temperature and greatest rise on the right side of the insulated vehicle. Its location at the forward edge of the front panel further indicates the residual impact of the engine heat.

Table 8

M2A3 Temperature Comparisons at Fort Benning (Oct. 18, 1999) and Fort Hood (Dec. 4, 2000)

Location	Benning A3 #2 Change	Hood A3 Change	Difference Oct-Dec
Interior Ambient Temperature	20.8	18.7	2.1
Flashlight Rack	50.7	42.8	7.9
Engine Caution Sign	61.0	56.3	4.7
Brake Release Sign	30.6	29.6	1.0
Wall Above Front Engine Access Panel	52.6	40.9	11.7
Hearing Caution Sign	56.6	37.1	19.5
Water Caution Sign	48.2	31.9	16.3
Cold Start Sign	53.3	33.6	19.7
M 16 Rifle Sign	36.1	19.4	16.7
Below Top Bracket	73.6	44.0	29.6
Night Goggles Sign	51.3	31.3	20.0
Below Second Bracket	77.8	42.8	35.0
6" Below Second Bracket	77.2	42.3	34.9
12" Below Second Bracket	76.6	39.0	37.6

In summary, based on these preliminary measurements of a vehicle with insulation on the engine access panel and wall, a difference was apparent. The December 2000 temperature data show a much slower rise in temperature, and one not out of line with the rest of the driver compartment, for the insulated vehicle, than was evident in September and October 1999. From a subjective perspective, also, the author sensed no radiator-like effect from the engine wall; the surfaces remained cool to the touch. It is important to remember, however, that the exterior ambient temperature was cooler in December; further measurements should be taken on warmer days.

Suggestions for Future Research

Further research is needed on heat in drivers' compartments. One area of research would include the effects of heat stress on BFV personnel. This focus would determine potential performance decrements to determine the effects of heat on cognitive functioning. The operational requirements of the Bradley driver necessitate vigilance, hand-eye coordination, visual acuity and rapid decision-making. Thus far, research into the effects of heat on these areas of functioning has yielded inconclusive results. A suggested reason for the inconsistencies is methodological variations in measurement and assessment of both heat and heat stress (Kobrick and Fine, 1983; Ramsey, 1995; Razmijou and Kjellberg, 1992). No research has yet been done to specifically investigate the interaction between the physical and cognitive demands placed on the driver, and how heat stress within the operational environment may impact upon these demands.

A systematic methodology is clearly needed to address these issues. This could entail use of, for example, the Walter Reed Performance Assessment Battery (PAB). The PAB was developed to assess changes in cognitive functioning over time and treatment levels (Thorne, Genser, Sing, and Hegge, 1985). It is a computer-based assessment, using a battery of cognitive functioning assessment instruments. The PAB can be configured to test reaction time, visual search and recognition tasks, logical reasoning, short-term memory, and mood and affect (Thorne et al., 1985). Each of these tasks has direct correlates in tasks performed by Bradley personnel. This or similar research would assess the true impact of excessive heat on occupants of armored vehicles.

Future investigations should also include another set of measurements on the insulated M2A3 vehicle, on a day in which the ambient external temperature is more typical of the Fort Hood or Fort Benning summertime highs. If the insulated panel continues to attenuate the high temperatures in the driver compartment, it should surely be adopted for all vehicles.

Conclusions

U.S. military personnel are required to accomplish difficult missions, often under extreme environmental conditions. Some of the most volatile areas are in desert environments, and the potential for deployment to these areas is relatively high. Bradley personnel have already distinguished themselves under extreme environmental conditions as were encountered in Operations Desert Shield and Desert Storm. This may prompt some to argue that there is no real need to deal with the effects of heat stress on performance. Bradley missions have historically been accomplished with resounding achievements. The argument may be made that as long as the missions are successfully completed there is no problem.

There is a certain amount of face validity to this assertion, but an analysis of costs to those performing these missions must be included in the equation. American soldiers can be relied upon to accomplish their mission, but the costs in terms of heat-related casualties and increased stress on the soldier may be excessive. It would seem a disservice to these soldiers to not consider ways to improve survivability and combat effectiveness, each of which may be degraded by exposure to environmental extremes.

In order to address the inconsistencies and disparities in the heat stress literature, an extensive review would be required, a task well beyond the scope of this report. However, it is clear from the existing evidence that some level of cognitive decrement is certainly produced by extreme thermal exposure, and may even result from exposure to thermal environments that would not be considered extreme. Therefore, it would be an informational asset to the military to understand the precise nature of the heat stresses that personnel in armored vehicles encounter, and the effect that heat stress has upon them.

Additionally, and most importantly, continued looks at the insulation of all armored vehicles could provide better solutions to reduce the already identified problems in driver compartments. The Bradley A3 is by no means the only vehicle with a too hot driver compartment. The ODS vehicle was shown hot; others are likely. Fully insulating the engine walls of all vehicles would be a start toward fixing the problem. The price paid for insulation would appear to be money well spent.

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Appendix A

Comparison Data

Note. Because of the iterative nature of the temperature measurements, not all locations had the same number of data points. Areas with asterisks represent some data anomalies; the original tables within the text should be consulted.

Legend
Hood A3 Vehicle #1, September 1999
Benning A3 Vehicles #1 and #2, October 1999
Hood A3 Insulated Vehicle #2, December 2000.

Location	Hood #1 start	Hood #1 end	Chg	Benning #1 start	Benning #1 end	Chg	Benning #2 start	Benning #2 end	Chg	Hood #2 start	Hood #2 end	Chg
Interior Ambient Temperature	79.4	100.5	21.1	70.7	90.5	19.8	68.2	89.0	20.8	52.6	71.3	18.7
Heater Controls	75.8	99.6	23.8	67.2	86.2	19.0	66.5	85.8	19.3	45.7	60.5	14.9
Waypoint Screen *	90.6	108.6	18.0	69.6	86.7	17.1	66.8	86.3	19.5	51.6	70.5	18.9
Steering Yoke	7.2	103.3	26.1	68.0	92.4	24.4	67.7	91.5	23.8	47.7	72.5	24.8
Inside of Hatch Cover *	100.7	111.4	10.4	65.4	97.5	32.1	65.1	91.7	26.6	42.5	63.0	20.5
Accelerator Pedal	81.9	102.8	20.9	67.6	91.2	23.6	67.1	93.3	26.2	47.2	70.7	23.5
Floor by Brake Pedal	83.5	103.0	19.5	67.8	86.2	18.4	68.7	85.4	16.7	46.3	71.5	25.2
Flashlight Rack*	110.5	123.1	12.6	68.9	118.3	49.4	67.6	118.3	50.7	56.5	99.3	42.8
Engine Caution Sign	80.4	149.5	69.1	68.2	132.1	63.9	67.5	128.5	61.0	63.2	119.5	56.3
Brake Release Sign	79.4	109.1	29.7	68.5	98.6	30.1	68.0	98.6	30.6	50.0	79.6	29.6
Wall Above Front Engine Access Panel*	109.5	136.5	27.0	67.8	119.8	52.0	66.9	119.5	52.6	55.9	96.8	40.9
Hearing Caution Sign	81.4	132.7	51.3	68.5	124.6	56.1	67.5	124.1	56.6	51.4	88.5	37.1
Water Caution Sign	81.4	125.1	43.7	69.2	115.8	46.6	67.2	115.4	48.2	49.3	81.2	31.9
Cold Start Sign	80.8	128.5	47.7	70.1	124.4	54.3	68.5	121.8	53.3	50.5	84.1	33.6
M 16 Rifle Sign	80.8	113.3	32.5	67.8	101.9	34.1	66.1	102.2	36.1	44.5	63.9	19.4
Wall Between Access Panels*	99.0	150.8	51.1	71.3	139.8	68.5	68.9	145.5	76.6	NA	NA	NA
Below Top Bracket *	101.7	150.8	49.1	69.1	118.4	49.3	66.7	140.3	73.6	51.8	95.8	44.0
Night Goggles Sign	80.0	122.4	42.4	68.4	115.8	47.4	66.3	117.6	51.3	48.6	79.9	31.3
Below Second Bracket *	109.3	152.5	43.2	68.8	119	50.2	67.4	145.2	77.8	51.2	94.0	42.8
6' Below * Second Bracket	112.9	148.2	35.3	72.0	143.8	71.8	68.6	145.8	77.2	49.9	92.2	42.3
12' Below * Second Bracket	111.6	137.8	26.2	72.6	139.8	67.2	69.3	141.8	76.6	49.2	88.3	39.0

Change in Temperature over the Course of a Day

Note. Because of the iterative nature of the temperature measurements, not all locations had the same number of data points. Areas with asterisks represent some data anomalies; the original tables within the text should be consulted.

Legend
Hood A3 Vehicle #1, September 1999
Benning ODS Vehicle, October 1999
Benning A3 Vehicles #1 and #2, October 1999
Hood A3 Insulated Vehicle #2, December 2000.

Location	Hood #1 A3 Change	Benning ODS Change	Benning A3 #1 Change	Benning A3 #2 Change	Hood #2 A3 Insulated Change
Interior Ambient Temperature	21.1	22.4	19.8	20.8	18.7
Heater Controls	23.8	25.7	19.0	19.3	14.9
Waypoint Screen*	18.0	NA	17.1	19.5	18.9
Steering Yoke	26.1	25.9	24.4	23.8	24.8
Inside of Hatch Cover *	10.4	41.2	32.1	26.6	20.5
Accelerator Pedal	20.9	28.3	23.6	26.2	23.5
Floor by Brake Pedal	19.5	23.6	18.4	16.7	25.2
Flashlight Rack *	12.6	47.6	49.4	50.7	42.8
Engine Caution Sign	69.1	62.7	63.9	61.0	56.3
Brake Release Sign	29.7	32.9	30.1	30.6	29.6
Wall Above Engine Access Panel *	27.0	46.3	52.0	52.6	40.9
Hearing Caution Sign	51.3	50.6	56.1	56.6	37.1
Water Caution Sign	43.7	44.2	46.6	48.2	31.9
Cold Start Sign	47.7	48.8	54.3	53.3	33.6
M 16 Rifle Sign	32.5	35.2	34.1	36.1	19.4
Wall Between Access Panels*	51.1	60.1	68.5	76.6	NA
Below Top Bracket *	49.1	51.3	49.3	72.6	44.0
Night Goggles Sign Area	42.2	33.2	47.4	51.3	31.3
Below Second Bracket *	43.2	58.4	50.2	77.8	42.8
6' Below Second Bracket *	35.3	60.3	71.8	77.2	42.3
12' Below Second Bracket *	26.2	59.1	67.2	76.6	39.0

Mean Change for Un-insulated and Insulated M2A3 Vehicles

Note. Because of the iterative nature of the temperature measurements, not all locations had the same number of data points. Areas with asterisks represent some data anomalies; the original tables within the text should be consulted. The mean value for points with asterisks is artificially low.

Legend
Hood A3 Vehicle #1, September 1999
Benning A3 Vehicles #1 and #2, October 1999
Hood A3 Insulated Vehicle #2, December 2000.

Location	Hood #1 Change	Benning #1 Change	Benning #2 Change	Mean A3 Change	Hood #2 Change
Interior Ambient Temperature	21.1	19.8	20.8	20.57	18.7
Heater Controls	23.8	19.0	19.3	20.7	14.9
Waypoint Screen *	18.0	17.1	19.5	18.2	18.9
Steering Yoke	26.1	24.4	23.8	24.77	24.8
Inside of Hatch Cover *	10.4	32.1	26.6	23.03	20.5
Accelerator Pedal	20.9	23.6	26.2	23.57	23.5
Floor by Brake Pedal	19.5	18.4	16.7	18.2	25.2
Flashlight Rack*	12.6	49.4	50.7	37.57	42.8
Engine Caution Sign	69.1	63.9	61.0	64.67	56.3
Brake Release Sign	29.7	30.1	30.6	30.13	29.6
Wall Above Front Engine Access Panel*	27.0	52.0	52.6	43.87	40.9
Hearing Caution Sign	51.3	56.1	56.6	54.67	37.1
Water Caution Sign	43.7	46.6	48.2	46.17	31.9
Cold Start Sign	47.7	54.3	53.3	51.77	33.6
M 16 Rifle Sign	32.5	34.1	36.1	34.23	19.4
Wall Between Access Panels*	51.1	68.5	76.6	65.4	NA
Below Top Bracket *	49.1	49.3	73.6	57.33	44.0
Night Goggles Sign	42.4	47.4	51.3	47.03	31.3
Below Second Bracket *	43.2	50.2	77.8	57.07	42.8
6' Below * Second Bracket	35.3	71.8	77.2	61.43	42.3
12' Below * Second Bracket	26.2	67.2	76.6	56.67	39.0